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Monitoring Solar-Thermal Systems: An Outline of Methods and Procedures

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ABSTRACT

This manual covers the fundamentals of monitoring solar thermal systems and addresses the varying requirements system owners may have when collecting energy production, plant performance, and operations and maintenance data. The reasons for implementing each level of monitoring are discussed, and examples of actual system monitoring are provided. Basic hardware for monitoring solar thermal systems is explained. Data collection and quality assurance are discussed, and sample operations and maintenance forms are provided.

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Monitoring Solar-Thermal Systems: An Outline of Methods and Procedures

INTRODUCTION

There may be many different objectives for implementing a program to monitor a solar thermal system. The kind of monitoring program selected and the level of effort spent on monitoring can be large or small depending on the needs of the system owner or operator. As an example, the owner of a large solar thermal plant may require a data acquisition system to obtain accurate measurement of the energy delivered or identify component failures as they occur. At the other end of the spectrum, a homeowner with a new solar hot water system may need only to keep a simple logbook of maintenance records to see if the system is performing as advertised and was worth the purchase price.

This manual discusses the technical issues associated with monitoring solar-thermal systems. It discusses some successful monitoring programs that have been implemented in the past. It gives the rationale for selecting a program of monitoring and gives guidelines for the design of new programs.

In this report, solar thermal monitoring systems are classified into three levels. For each level, the report discusses the kinds of information obtained by monitoring, the effort needed to support the monitoring program, the hardware required, and the costs involved.

Ultimately, all monitoring programs share one common requirement: the collection of *accurate data* that characterize some aspect or aspects of the system under study. This report addresses most of the issues involved with monitoring solar thermal systems. It does not address such topics as design fundamentals of thermal systems or the relative merits of the many different technologies employed for collection of solar energy.

WHY MONITOR A SOLAR-THERMAL SYSTEM?

Both large and small solar-thermal systems are in widespread use meeting the energy needs of institutional, industrial, and residential users. Most system designs are not new. Effective designs for collectors that convert sunlight to

thermal energy for practical use have been around since the start of the 20th century.

The owner or operator of a solar-thermal system can have many reasons for monitoring the system. Generally, any monitored parameter can be grouped into one of three categories: 1) data collected to record energy production; 2) data collected to characterize system or sub-system performance; 3) data collected to record system reliability. The data collection mechanism can be as complex as an automated, computer-based data acquisition system or as simple as handwritten records kept in a logbook.

DATA COLLECTED TO MONITOR ENERGY PRODUCTION

The generation of sensible thermal energy is the purpose of every solar-thermal system. Not surprisingly, energy production is the most common parameter measured by the operators of these systems. Energy can be measured directly with a recording BTU meter or, alternatively, the amount of energy produced can be calculated from measurements of flow and temperature (definitions and equations are given in Appendix A). The reasons for measuring energy production will vary.

For example, 35% of U.S. households presently use electricity to heat water (1), and utilities have begun to evaluate Solar Domestic Hot Water (SDHW) as an effective Demand Side Management (DSM) measure. To do this, utilities require actual data that show how much hot water is used by a typical household throughout the day and how the SDHW system meets some of that load. In particular, the production of energy by the SDHW system at times of peak utility demand can be measured to assess load management. The best solution to this monitoring requirement is to use a dedicated datalogger that collects, time stamps, and records data for an extended period of time.

Often, a simple daily or weekly record of energy produced is sufficient. In these cases, a BTU meter is installed and a program is initiated in which an operator reads the meter once per period and records the readings in a logbook. The period of recording may be daily, weekly, or monthly.

DATA COLLECTED TO CHARACTERIZE SYSTEM PERFORMANCE

When a solar-thermal system is of a new or unusual design, the operator may be interested in knowing more than simple system energy production. A monitoring system that determines system efficiency, particularly over a range of operating conditions, is then utilized. The information yielded by this kind of monitoring can uncover system design shortcomings or test upgrades in hardware or software. In addition, long-term collection of this kind of data can reveal system performance degradation trends that take months or years to develop.

Characterization of system performance requires sensors that monitor the ambient conditions of irradiance, temperature, and wind at the solar array as well as the array operating parameters of temperature and flow. The rate at which the data are recorded (e.g. hourly, half-hourly, etc.) must be selected to capture the transients of interest that occur during system start-up and shut-down conditions.

Monitoring a system in actual use in the field provides information not available during standard or controlled laboratory tests. Specifically, monitoring reveals the following:

- operation at all (not just ideal) solar conditions
- thermal energy duty cycle (cycling patterns with real loads)
- field performance of systems used by trained or untrained operators

When data have been collected over a sufficient period of time, system information can be determined from:

- collector or subsystem efficiency
- loss rates of various subsystems
- storage capacity effectiveness
- energy delivery versus time of day and load
- net per annum energy delivered by the system

DATA COLLECTED TO RECORD SYSTEM RELIABILITY

System reliability is a function of system design, installation, quality of the hardware, and use. A comprehensive logbook of all downtime and maintenance actions is an essential part of a complete system maintenance program. Review of the logbook can determine the presence and rate of repeated failures of various components (e.g. valves, seals, etc.) and it can be used to cross-reference reductions in energy production recorded elsewhere by BTU meters.

At a minimum, an entry is made in the logbook whenever downtime occurs or maintenance is undertaken. The logbook can also be used within a program of regular inspections. In this application, site operators use the logbook to record inspection results. Suspect performance of key system components can be used to prevent failures before they occur.

THE THREE LEVELS OF SYSTEM MONITORING

Monitoring a solar-thermal system can be performed with or without dedicated hardware, via continuous data recording or periodic operator inspection, and with or without a major investment of labor and dollars. The level of monitoring selected is dictated by several factors: the kind of information required; the expertise of the personnel available to run the monitoring program; the accessibility of the system to monitoring; and the budget available for hardware and labor to support the project.

Three levels of monitoring have been designated. These are described as follows:

- I. Level I comprises continuous monitoring of the system by an on-site Data Acquisition System (DAS). The DAS automatically records sensor readings of solar irradiance, ambient temperature, wind speed, fluid flow, operating temperatures and, possibly, BTU. The sensor data are supplemented with an Operations and Maintenance (O&M) logbook kept by the site operator. With this level of monitoring, accurate performance information (e.g. efficiency

curves) can be obtained as well as time-of-day production for utility load matching requirements.

- II. Level II monitoring consists of a BTU meter (or other metering for energy production) and an O&M logbook. A history of the overall production and system reliability can be generated with this level of monitoring, though no performance or time-of-day information is available.
- III. Level III monitoring is the most simple, consisting of a logbook of O&M information on the system under test. This kind of monitoring is the least expensive and is appropriate for monitoring off-the-shelf solar systems for which performance is well defined and production data are not needed.

Each of the three levels of monitoring is described below. For each level, the kind of information gained by monitoring is discussed.

THE LEVEL I MONITORING SYSTEM

Level I monitoring is most often used with large, solar-thermal systems or with prototype systems placed under long-term evaluation. Monitoring at this level requires a dedicated datalogger that reads and records the outputs from many sensors. The datalogger provides three important functions: 1) it digitizes sensor output signals and converts them to engineering units; 2) it records maximum, minimum, and average values for later retrieval; 3) it calculates quantities such as

efficiency and BTUs. For maximum flexibility, the datalogger can be made accessible via telephone modem. This allows the datalogger to be reprogrammed or monitored in real-time or the data to be collected without a site visit.

An example of Level I monitoring is the DAS used to monitor the solar process heat system installed at the California Correctional Institution in Tehachapi, California. The system and DAS were installed in early 1991. On a typical summer day, energy delivery for this system can exceed 31 million BTU (9100kWh) of heat. The DAS was designed to monitor all important aspects of system performance and ambient conditions. The monitored parameters and instrumentation are given in Table 1.

The Tehachapi Level I DAS is equipped with more than the minimum instrumentation required to monitor system performance. For example, this DAS has instruments that measure all three components of incident sunlight: direct normal, diffuse, and global. For complete performance characterization of concentrating arrays, only the direct normal need be measured. Similarly, flat-plate collector performance is most often calculated based on the readings of a single pyranometer mounted in the plane of the collector array. (An alternative to this is to use a horizontally mounted pyranometer and model the irradiance received in the collector plane with geometry.)

A dedicated datalogger records all sensor signal inputs, converts these raw signals to engineering units, and stores average, maximum, and minimum values of these readings every half-hour.

Table 1. Tehachapi Level I DAS Input Signals

Signal Description	Sensor
Horizontal Irradiance	Eppley Precision Spectral Pyranometer (PSP)
Direct Normal Irradiance	Eppley Normal Incidence Pyrliometer (NIP)
Diffuse Irradiance	Eppley Shadow Band Stand and PSP
Relative Humidity	Phys-Chem PCRC-11 RH Sensor
Ambient Temperature	Fenwal Electronics UUT51J1 Thermistor
Wind Speed	Met-One 014A Wind Speed Sensor
Wind Direction	Met-One 024A Wind Direction Sensor
Flow	Orifice Plate and Rosemount 1151DP4E12M2 Flow Transmitter
Inlet Fluid Temperature	Omega NB1-Cass-144-6 Type E Thermocouple
Outlet Fluid Temperature	Omega NB1-Cass-144-6 Type E Thermocouple

The datalogger used in the Tehachapi Level I DAS is the Campbell Scientific, Inc., 21X. This datalogger was selected because it met the requirements for number of input channels, data resolution, availability of output ports, computational capability, and outdoor rating. In the section covering DAS Instrumentation, more information is given on datalogger features and the criteria for selecting a datalogger.

In addition to recording sensor data, the datalogger of a Level I system can be used to perform calculations such as system efficiency in real-time. This service is of great value in on-site troubleshooting and during the performance of short-term performance tests.

In Tehachapi, for example, the datalogger is programmed to calculate energy (BTU) production and system efficiency in real-time. The first step in the calculation of system energy is the determination of the density of the working fluid based on inlet temperature. Next, the specific heat of the working fluid is calculated based on the inlet and outlet temperatures. Mass flow is calculated from the pressure drop across the orifice plate and the fluid density. Finally, knowing mass flow, specific heat, and temperature difference, the system's instantaneous power and energy production are calculated. This value is available during either on-site testing or via modem for real-time monitoring as a check of system integrity when hardware failures are suspected. This is a parabolic-trough concentrating system that focuses only the sun's direct rays. Determination of system efficiency requires calculation of the actual direct irradiance in the plane of the collectors. For this calculation, the determination of the solar elevation and azimuth are computed based upon time of day and day of the year. Ultimately, the incidence angle between the sun's position and the array plane is found and used to correct the data obtained by the pyrheliometer to obtain true direct irradiance in the plane of the array.

This DAS is accessible by telephone modem, allowing complete data collection from off-site locations. In addition, the datalogger can be reprogrammed or monitored in real-time from off-site as well.

The data from this system are used in several ways (3):

- To accurately determine energy delivery
- To determine instantaneous and long-term efficiency values for the system
- To identify deficiencies in the original design that impact performance
- To evaluate the effects of design upgrades made to the system over several months
- To establish a database of actual operations data useful for system modeling

Figure 1 presents some of the performance data collected by the Tehachapi Level I DAS on 14 July 1991.

In addition to the DAS data, the Tehachapi Level I monitoring program incorporates a comprehensive O&M logbook kept by the site operators. Each downtime event is listed in this book along with the causes of downtime and any actions taken. Planned maintenance actions are also documented as they are performed. The data from a comprehensive logbook of this kind can be used to record or derive the following:

- labor cost and man-hours spent on maintenance actions
- component failure rates
- system O&M cost
- energy and revenue lost due to planned and unplanned downtime
- system availability
- system capacity factor

THE LEVEL II MONITORING SYSTEM

Level II monitoring is used on smaller solar-thermal systems, on systems for which performance data are not required, or where funding for Level I monitoring is not available. The primary information obtained through Level II monitoring is the total production of thermal energy and the long-term reliability of the system. By giving up the dedicated datalogger, the cost for monitoring hardware is greatly reduced as is the cost for data collection and subsequent analysis.

A Level II system consists of a method of metering solar BTU generation whose output is manually recorded at regular intervals by the site operator. The data can be recorded daily, weekly, or monthly, as desired.

Figure 1. Collector Temperatures and Flow Rate for Tehachapi, 14 July 1991.

An example of successful Level II monitoring is the program implemented by Gould Electronics, Inc., for their medium-temperature solar Industrial Process Heat (IPH) system. The IPH system was designed and constructed by Solar Kinetics, Inc., in 1982. The system consists of 432 line-focusing parabolic-trough collectors with a total aperture area of 60,480 ft².

The IPH system ran successfully for several years but, by 1990, recurring failures resulting in low system availability and capacity threatened to force Gould to shut it down. At that time, engineers from the Solar Thermal Design Assistance Center at Sandia National Laboratories were consulted. Working together, Gould and Sandia developed a three-phase approach to identify and solve the system's technical problems (4).

In phase one, critical elements of the hardware were redesigned and retrofits installed. At this time, Level II system monitoring began. A Hersey Model™ 7020 BTU meter was installed to record system energy production (see Table 2). Also, a monthly logbook was started in which records of several field performance parameters were kept. The monitored parameters included the number of days the system operated, total BTUs generated, maintenance,

manpower costs, materials costs, and net energy cost savings.

With Level II monitoring, accurate records of plant energy production and O&M manpower and materials costs allowed Gould and Sandia engineers to determine the effectiveness of the plant refurbishment program.

Today, the IPH system is operating at over 90% equipment availability and returning to Gould a net energy cost savings of approximately \$7,500 per month.

THE LEVEL III MONITORING SYSTEM

Level III monitoring is the least expensive system to implement. It is applicable for small off-the-shelf systems where general system performance is already known and the production output is not needed. Level III monitoring consists of a standard O&M record kept by the site operator. The information obtained by this level of monitoring is a reliability record of the system and its components in the actual setting and conditions of real-world use.

Table 2. BTU Meter: Hersey™ Model 7020

Parameter	Specifications
Accuracy	± 0.5%
Power Supply	120 vac, with Battery Backup
Flow Rate Input	Sine Wave, Pulse, or 4-20 mA Transmitter
Temperature Input	100 ohm RTDs (2°F to 350°F)
Flow and BTU Output	Contact Closure or TTL Pulse Train
Display	Six Digit, Continuous LCD, Resettable
Enclosure	NEMA 4X

Level III monitoring is often asked of untrained homeowners participating in a utility or government sponsored study. The accuracy of the log entries is always a concern in this type of program. The use of structured log-entry forms greatly facilitates this process. Examples of typical logbook entry forms are shown in Appendix B.

Level III monitoring can be used to perform reliability studies. Specifically, the following kinds of information can be gained from accurate logbook records:

- comparisons of system reliability in different locations
- installer comparisons
- the level of owner involvement in system reliability
- repair costs and frequency of downtime
- satisfaction comparisons between owners

The Commonwealth of Virginia is presently undertaking a program to monitor and evaluate several photovoltaic and solar-thermal systems at all three levels. The Level III monitoring will be performed at two Juvenile Residence Cottages equipped with Solar Domestic Hot Water (SDHW) systems.

Under the Level III monitoring program being developed by Virginia Polytechnic Institute (VPI), a custom O&M logging form will be provided to each site operator. These forms will be designed to guide the site operators through the task of effective record keeping. A schedule for making log entries will be established by VPI

and hands-on training in standard reporting formats and procedures will be given. The program's goal is to obtain detailed information on system failures, effective repair procedures, costs associated with failures, and the overall effectiveness of general O&M measures. VPI faculty and graduate students will review all of the collected logbook sheets and collate the data to yield year-long summaries of system costs and reliability.

DAS INSTRUMENTATION OVERVIEW

While a complete description of all the hardware and instrumentation used to monitor solar thermal systems is beyond the scope of this manual, this section provides a description of the more common instruments and their use. The strengths and weaknesses of the various sensors are described as well as the relative cost of each.

TEMPERATURE SENSORS

Many different instruments are used to measure temperature. The three most common types are:

- thermocouples
- platinum Resistance Temperature Detectors (RTDs)
- thermistors

Table 3 compares some of the advantages and disadvantages of the three commonly used temperature sensors.

Table 3. Comparison of Temperature Sensors

	Thermocouple	RTD	Thermistor
ADVANTAGES	Self-powered	Most stable	High output
	Simple	Most accurate	Fast response
	Rugged	More linear than thermocouple	Most sensitive
	Inexpensive		
	Wide temp. range		
DISADVANTAGES	Nonlinear	Expensive	Highly nonlinear
	Low voltage	Self-heating	Fragile
	Reference needed	Current source needed	Limited temp. range
	Least sensitive		Current source needed

Thermocouples generate a voltage based on the Seebeck effect: two wires of dissimilar metals joined at one end develop a voltage related to the temperature of the junction. For small changes in temperature, the Seebeck voltage is nearly linear. Different thermocouple pairs are commercially available offering a wide range of operating temperatures.

Resistance Temperature Detectors (RTDs) operate on the principle that the resistivity of metal changes with temperature. Platinum and nickel are the metals most often used in RTD construction. When high reliability is required, platinum is usually selected.

Thermistors are generally composed of semiconductor materials having a negative temperature coefficient; that is, their resistance decreases with increasing temperature.

In fluid-filled systems, the temperature sensing device is placed in a thermowell. Thermowells are corrosion-resistant sleeves that allow the sensing element to project into the flowing fluid for accurate reading.

FLOW SENSORS

Many types of flow sensors are available for use in solar thermal DASs. In general, the sensors can be classified as differential pressure, positive displacement, velocity, and mass-flow meters (6).

Differential pressure flowmeters are the most common units in use today. The basic principle of operation is that a flowing fluid experiences a pressure drop as it passes through a restriction proportional to the square of the flow rate. A secondary, pressure-measuring element is necessary to provide the signal that is converted to a flow value. Sensors of this type include orifice plates, venturi tubes, flow nozzles, pitot tubes, and elbow meters. Orifice plates are the most common flowmeters in use and consist of a flat piece of metal with a precise hole bored in it. The pressure drop across the orifice is measured and translated into a flow value based on the orifice diameter and the properties of the fluid.

Positive displacement meters operate by separating liquids into measured increments and passing them on. Positive displacement meters are often used to measure flows of viscous

liquids. Sensors of this type include reciprocating piston meters, oval-gear meters, and rotary vane meters. Rotary vane meters are operated with a rotating impeller mounted inside the meter's housing. A fixed volume of liquid is swept to the meter's outlet from each compartment as the impeller rotates; impeller rotations are counted via a magnetic pick-up.

Velocity meters operate linearly with volume flow rate. Sensors of this type are turbine meters, vortex meters, and ultrasonic flowmeters. Turbine meters are in widespread use. A turbine meter consists of a multi-bladed rotor within a pipe mounted perpendicular to the direction of flow. As the moving fluid spins the rotor, a magnetic pick-up or photoelectric sensor counts and totals the revolutions. The number of revolutions in a given period of time is directly proportional to flow volume.

Mass flow meters are designed to measure the mass rate of flow directly, as opposed to flow volume. Meters of this type include coriolis meters and thermal mass flow meters. Coriolis meters are the more common of the two and operate by measuring the fluid forces on a vibrating u-shaped tube. The measured force is directly proportional to mass flow rate, and no compensation is needed for changes in temperature or pressure of the fluid.

Table 4 lists some operating characteristics of the more common flow sensor types (7).

BTU METERS

BTU meters are microprocessor-based instruments that calculate and display the energy delivered by a flowing liquid. These meters require a flow sensor to measure flow rate of the working fluid. They also require temperature sensors at the inlet and outlet of a device such as a heat exchanger. The microprocessor within the meter calculates BTU from these sensor readings and generally displays a counter with the total energy produced since the last instrument reset. Typical cost for a commercial BTU meter with sensors is \$2000 to \$3000.

PYRANOMETERS

Instruments for measuring total (beam+diffuse) irradiance are known as pyranometers. Pyranometers are used to measure the irradiance available to flat-plate collectors. Concentrating collectors use only the direct normal component of sunlight (see the section on Pyrheliometers that follows). Pyranometers generally fall into one of two categories: thermopile-based instruments and semiconductor-based instruments.

A thermopile is a multijunction thermocouple. Thermopile-based pyranometers generally use a sensing thermopile that is coated with optical black. Temperature rise of

Table 4. Comparison of Flow Sensors

Flowmeter Element	Usable Service	Pressure Loss	Typical Accuracy (%)	Viscosity Effect	Relative Cost
Orifice Plate	Clean, dirty liquids	Medium	± 2.0 to ± 4.0 of full scale	High	Low
Turbine	Clean, viscous liquids	High	± 0.25 of rate	High	High
Vortex	Clean, dirty liquids	Medium	± 1.0 of rate	Medium	High
Ultrasonic (time-of-travel)	Clean, viscous liquids	None	± 1.0 to ± 5.0 of full scale	None	High
Mass (Coriolis)	Clean, dirty, viscous liquids	Low	± 0.4 of rate	None	High

the thermopile is proportional to the sunlight intensity shining on the instrument. Temperature compensation circuitry is used to minimize the effects on the reading of changes in ambient temperature. Thermopile-based pyranometers offer excellent linear response to all wavelengths of visible light. The figure of $\pm 2\%$ is often used to express the accuracy of thermopile pyranometers.

The short-circuit current output of a PV cell is a reasonably linear function of incident solar energy. Silicon pyranometers are less expensive than thermopile-based units but have two shortcomings. The first is that silicon is not equally sensitive to all wavelengths of visible light. The second is that silicon pyranometers are not usually temperature compensated, leading to errors associated with varying conditions over time. Silicon pyranometers produce data accurate to approximately $\pm 5\%$.

Semiconductor-based pyranometers use a small photovoltaic (PV) cell to measure irradiance. The short-circuit current output of a PV cell is a reasonably linear function of incident solar energy. Silicon pyranometers are less expensive than thermopile-based units but have two shortcomings. The first is that silicon is not equally sensitive to all wavelengths of visible light. The second is that silicon pyranometers are not usually temperature compensated, leading to errors associated with varying conditions over time. Silicon pyranometers produce data accurate to approximately $\pm 5\%$.

PYRHELIOMETERS

Instruments that measure the sun's direct rays (direct normal irradiance) are known as Normal Incidence Pyrheliometers (NIP). The conventional NIP uses a thermopile collector at the bottom of a collimating tube. Typical accuracy for a thermopile-based pyrheliometer is $\pm 0.5\%$.

The NIP must be accurately pointed at the sun at all times. A solar tracker is used to do this. Two kinds of solar trackers are available: trackers requiring frequent (daily) manual alignment; and microprocessor-based trackers that require only yearly alignment. The microprocessor-based tracker is more expensive

than the manually aligned model, but is often used in remote or unmanned locations.

In the past few years, a new instrument has become available to measure direct normal irradiance; the Rotating Shadow Band pyranometer (RSB). At present, two manufacturers make RSBs. Both use a fixed, horizontal silicon detector and a radial arm that regularly sweeps over the detector shading it. This method of unshading and shading the detector provides direct readings of the global horizontal and global diffuse irradiance. Based on these two readings and the position of the sun, each RSB uses an on-board microprocessor to calculate the direct normal component of the sunlight. RSB instruments have the advantage of not requiring periodic alignment. Their overall accuracy is about that of the silicon detectors that each uses.

DATALOGGERS

Dataloggers digitize analog sensor signals and convert them to engineering units. Table 5 lists some of the key questions that must be answered when selecting a datalogger.

Dataloggers can be stand-alone programmable units, printed circuit cards that are inserted into commercial bus-based instruments, or simple dedicated analog-to-digital converters that attach to the serial or parallel port of a PC. Table 6 gives an example of each of the three types of datalogger and some of the key design specifications for each unit. No single datalogger is best for all applications.

DATA QUALITY ASSURANCE

Before data can be used for analysis, some form of validity checking must be performed. This validity checking, called Quality Assurance (QA), is essential to the process of data collection. Without it, erroneous data may be included in the analysis and false conclusions may be drawn.

There can be many sources of erroneous DAS data. Some of these are:

- sensors out of calibration
- failed sensors
- failed wiring or connectors
- failed signal conditioning components

Table 5. Datalogger Specification Questions

Design Parameter	Questions
Power Requirement	Is ac available? Is battery backup required?
Temperature Rating	Is outdoor temperature rating required?
Surge Protection	Is on-board surge protection provided?
Analog Inputs	Are sufficient differential/single ended analog inputs provided? Can the number be increased with external multiplexing?
Pulse Inputs	Are pulse counting inputs required?
Outputs	Are analog outputs required? Are digital outputs required? Are control functions required following alarm conditions?
Storage	Is sufficient on-board storage provided?
Access	Is modem communication supported? Will RF communication be required?
Data Sample Rate	Is high speed sampling required?
Computational Ability	Is the datalogger capable of arithmetic computations?

- induced electrical noise
- improper installation or use of sensors

Identifying DAS component failures is generally easier than recognizing out of calibration conditions. A failed element usually (though not always) results in a signal that is either zero or impossibly large which does not vary as expected. Recognizing an out-of-calibration state for a sensor requires careful analysis, described below.

Proper QA identifies data that are unquestionably false or suspected of being inaccurate. There are different ways to approach QA, but essentially, all QA amounts to comparing each recorded data point against a range of values that may be *reasonably expected* for that signal at that time. Determining the range of acceptable values for a signal at a given time is the difficult part of QA.

Two methods of establishing QA ranges can be used: unconditional or conditional methods.

Unconditional QA performs two functions: it establishes that the proper number of data records and fields are present in the collected data; and it compares these data against the

maximum acceptable range limits for each signal.

The check for record completeness is an essential step that must be performed prior to any other QA. The process consists of recognizing the absence of records that should be in the data file and identifying the presence of records that are duplicates of those already in the data file. Files may miss records when the data collection is intermittent and an improperly long time elapses between collections. Duplicate records can be collected when communication problems with data collection hardware have problems and retries are initiated. In either case, the goal is a resulting file with the proper number of unique data records.

Unconditional QA limits are established based on the manufacturer's specifications for each sensor in the system and on specific knowledge of the environment in which each sensor is used. Unconditional ranges are always valid. As an example, a properly functioning irradiance sensor yields a zero value in total darkness and positive values when illuminated. The unconditional lower limit for an irradiance sensor is, therefore, set to zero. Any negative reading is flagged as false. Care must be taken

Table 6. Selected Datalogger Comparisons

	21X Campbell Scientific	Micro-440e Blue Earth Research	DAS-16 Keithlery/Metrabyte
Analog Input			
Number of Channels	16 SingleEnded 8 Differential	8 SingleEnded	16 SingleEnded/ 8 Differential
A/D	14 bit	8 bit	12 bit
Common Mode Range	± 5 Vdc	0 to 5 Vdc	± 10 Vdc
Sample Rate	2.4 ms	40 µs	20 µs
Pulse Input			
Number of Channels	4 Eight Bit <or> 2 Sixteen Bit	None	None
Analog Output			
Number of Channels	4 Switched 2 Continuous	2 Continuous (Auxiliary Module)	2 Continuous
Digital Output			
Number of Channels	6 TTL Channels	14 TTL Bidirectional Channels	4 TTL Outputs 4 TTL Inputs
Display	8 Digit LCD	7 Segment LED	None
Transient Protection			
Input Chan.	Spark Gaps	None	None
Power Supply	12V Power: Transorbs	None	None
Processor	Hitachi 6303	80C51FA	None
Memory	32K ROM, 64K RAM	32K ROM, 32K RAM	None
Current Drain	25 mA @ 12 V	70 mA @ 12 V	800 mA @ 5 V
Environmental	-25 to +50°C	0 to +50°C	0 to +50°C
Comments			
	Stand alone unit Internal 12V battery 1 Serial Port Cost: \$2090	Program in BASIC External 12V supply 2 Serial Ports Cost: \$319	PC Bus Card High Speed DMA 3 Channel Timer Cost: \$999

when establishing the unconditional QA limits. For example, the manufacturer may specify a pump to deliver 150 gpm. At times, however, this pump may actually deliver 155 gpm. Setting the upper limit of the flow signal to the specified value will then result in rejection of valid data. In practice, the unconditional QA

ranges are usually set conservatively and then narrowed as operational experience is gained with the actual system.

Conditional QA establishes range limits for a signal based on the values of other signals *at that time*. Conditional QA ranges are calculated

based on knowledge of the characteristics and performance of the system's components. The first step in using conditional QA is establishing that the applicable conditions exist in a data set. This is done with an If-Then approach. Once the condition is established, the range limits can be calculated and the data test performed.

To illustrate; suppose a nominally 50% efficient thermal collector with an area of 1 m² is instrumented with a pyranometer, flow meter, and inlet and outlet temperature sensors. One could test the validity of the two temperature readings based on the readings of the pyranometer and flow meter. The first step would be to validate the pyranometer and flow readings. Next, if these readings are valid, a conditional QA range could be calculated when the following conditions are met:

If (irradiance > 400 W/m²) and (flow > 4 l/m for at least 5 minutes)

The test performed would evaluate the equation of efficiency A1.2b

$$\eta_a = [(mc_p/A_a) (t_{f,e} - t_{i,i})] / I \quad (A1.2b)$$

Rearranging terms, we get the following:

$$(t_{f,e} - t_{i,i}) = \eta_a A_a I / (m c_p) \pm \Delta t$$

Lookup tables would be used to supply the values of c_p and ρ (needed to convert flow into mass flow). Then, knowing nominal efficiency (0.5), collector area (1 m²), and irradiance (I), an expected value for the temperature gain, $(t_{f,e} - t_{i,i})$, would be determined. A value of Δt would

be added and subtracted to this calculated value to provide the *range* of acceptable readings for this quantity. The value for Δt would be determined based on experience with the system. If the quantity fails the conditional QA test, then a flag is set in the data record. Further examination is required to identify which of the temperature readings is false.

CONCLUSIONS

Monitoring of solar thermal systems may be required by plant owners, utility companies, system designers, or government agencies. In every case, the goals of the monitoring program determine the level of monitoring that should be implemented. The goal of a reliability study may be met with inexpensive record keeping by a plant maintenance engineer. At the other extreme, continuous data logging by dedicated hardware may be required to assess system efficiency at all operating conditions for extended periods of time.

Effective system monitoring can be utilized to meet many goals:

- to verify system design or identify faulty or inadequate subsystems
- to study energy load and system energy delivery for demand side management
- to assess performance for warranty purposes
- to determine long-term reliability
- to develop appropriate O&M schedules

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Appendix A Review of Solar Collector Performance Equations

THERMAL EFFICIENCY

When a solar collector is operating under steady-state conditions, the relationship that governs thermal performance is:

$$\begin{array}{ccccccc} \text{the rate of} & & \text{the rate of} & & \text{the rate of} & & \text{the rate of} \\ \text{energy} & & \text{energy} & & \text{energy loss} & & \text{energy} \\ \text{extracted} & = & \text{absorbed in} & - & \text{from the} & = & \text{carried} \\ \text{from the} & & \text{the collector} & & \text{collector} & & \text{away by} \\ \text{collector} & & \text{by the absorber} & & \text{by conduction,} & & \text{the transfer} \\ & & & & \text{convection, and} & & \text{fluid} \\ & & & & \text{radiation} & & \end{array}$$

For flat plate collectors, this equation is expressed as (6):

$$q_u / A_a = F_R [I_a (\tau \alpha)_e - U_L (t_{f,i} - t_a)] = (\dot{m} c_p / A_a) (t_{f,e} - t_{i,i}) \quad (A1.1a)$$

where:

- A_a = aperture area of the collector, m^2
 c_p = specific heat of the transfer fluid, $J/kg \cdot s$
 F' = absorber plate efficiency factor, dimensionless, defined as (8):

$$F' = \frac{\text{heat transfer resistance from absorber to ambient air}}{\text{heat transfer resistance from fluid to ambient air}}$$

- F_R = the collector heat removal efficiency factor, a dimensionless coefficient equal to the energy collected divided by the energy that would be collected if the entire plate were at inlet fluid temperature. F_R is defined as (8):

$$F_R = \dot{m} c_p / U_L [1 - \exp(-F' U_L / \dot{m} c_p)]$$

- I_a = available solar irradiation incident upon the collector, per unit area, W/m^2 ;
 [For flat-plate and evacuated-tube, I_a = global irradiance on the collector plane;
 for concentrating collectors, I_a = direct normal irradiance on the collector plane.]

- $\dot{m}$ = mass flow rate of the transfer fluid, kg/s
 η_o = optical efficiency of collector ($\tau \alpha$ for a flat plate)
 q_u = rate of useful energy extracted from the collector, W
 t_a = ambient air temperature, $^{\circ}C$
 $t_{f,e}$ = temperature of the transfer fluid leaving the collector, $^{\circ}C$
 $t_{f,i}$ = temperature of the transfer fluid entering the collector, $^{\circ}C$
 U_L = heat transfer loss coefficient for the collector, $W/m^2 \cdot ^{\circ}C$
 $(\tau \alpha)_e$ = effective transmittance-absorptance product for the collector

Equation A1.1a applies to all types of collectors. However, at higher temperatures, such as parabolic troughs, the variation of U_L with temperature becomes significant. A second-order equation is used (9):

$$q_u / A_a = F_R \eta_o I_a - U_{L,1}(t_{f,i} - t_a) - U_{L,2}(t_{f,i} - t_a)^2 \quad (A1.1b)$$

COLLECTOR EFFICIENCY

The efficiency of the collector, η_a , can be expressed as:

$$\eta_a = [F_R I (\tau \alpha)_e - F_R U_L (t_{f,i} - t_a)] / I \quad (A1.2a)$$

or

$$\eta_a = [(\dot{m} c_p / A_a) (t_{f,e} - t_{i,i})] / I \quad (A1.2b)$$

TYPICAL COLLECTOR EFFICIENCY CURVE

In graphic terms, the equation above represents a straight line. The vertical axis represents efficiency, η , and the horizontal axis represents $(t_{f,i} - t_a)/I$. Figure A.1 presents typical solar-noon instantaneous efficiency curves for 4 types of collectors: two flat plate; an evacuated tube; and a parabolic trough (9).

Note that the line representing efficiency slopes downward at a rate of $F_R U_L$. Note also that maximum efficiency occurs when $(t_{f,i} - t_a)/I$ is zero. Thus, the lowest value that can be obtained for this expression is desirable for maximum efficiency. Unfortunately, only $t_{f,i}$ is under any control of the user. One must conclude that using the lowest practical operating temperature yields the most energy gain from the collector.

Figure A.1. Typical Collector Instantaneous Efficiency Curves.

Appendix B

Sample O&M Logbook Forms

B.1 Industrial or Commercial System (professionally maintained).

B.2 Residential system (homeowner).

Site	Date	Report Number
Type of Maintenance: ☐ Scheduled Maintenance ☐ Unscheduled Maintenance ☐ Emergency Repair		
Event Description: _____ _____ _____		
Action Taken: ☐ Adjustment ☐ Test ☐ Repair ☐ Replacement ☐ Inspection Notes: _____ _____		
Subsystems Involved: <div style="display: flex; justify-content: space-around; margin-top: 10px;"> <div>☐ Collector</div> <div>☐ Tracker</div> <div>☐ Plumbing</div> <div>☐ Electrical</div> <div>☐ Metering</div> </div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> <div>☐ Structural</div> <div>☐ Heat Exchanger</div> <div>☐ Pump</div> </div>		
Problem Occurred: Date _____ Time _____	Action Completed: Date _____ Time _____	System Off-Line? ☐ Yes ☐ No Downtime Hours _____
Parts Replaced: _____		
Labor: Repair Hours _____ Crew Size _____ Manhours _____		
Status: Work Complete? ☐ Yes ☐ No <div style="margin-left: 100px;"> Notes: _____ _____ </div>		
Report Completed By: _____		

Figure B.1. Sample Level I O&M Logbook Form.

Maintenance and Inspection Report							
Site	Date		Report Completed By:				
Visual Inspections:							
<u>Subsystem</u>	<u>Status</u>		<u>Problem Description</u>				
Collector	☐ OK	☐ Problem	☐ Fogging	☐ Leakage	☐ Broken Glass	☐ Crazing	
Plumbing	☐ OK	☐ Problem	☐ Leakage	☐ Frozen Pipe	☐ Corrosion	☐ Open Valve	
Controls	☐ OK	☐ Problem	☐ Burned Switch	☐ Broken Wire	☐ Failed Connector		
Storage System	☐ OK	☐ Problem	☐ Leaking Tank		☐ Failed Heating Element		
Structure	☐ OK	☐ Problem	☐ Broken Support		☐ Rust	☐ Loose Mount	
Extra Notes: <div style="border-bottom: 1px solid black; height: 15px; margin-bottom: 5px;"></div> <div style="border-bottom: 1px solid black; height: 15px; margin-bottom: 5px;"></div>							
Maintenance and Repair:							
(Examples: Replace Filter, Paint, Flush Tank, Replace Anode Rod, etc.) General Maintenance Action <div style="border-bottom: 1px solid black; height: 15px; margin-top: 10px;"></div> <div style="border-bottom: 1px solid black; height: 15px; margin-top: 10px;"></div>							
(Examples: Repair pipe leak, Replace stuck valve, etc.) Emergency Repair or Replacement: <div style="border-bottom: 1px solid black; height: 15px; margin-top: 10px;"></div> <div style="border-bottom: 1px solid black; height: 15px; margin-top: 10px;"></div>							
Parts Replaced: 							

Figure B.2. Sample Level III O&M Logbook Form.

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